

## Characterization, Concentrations and Emission Rates of Volatile Organic Compounds from Two Major Landfill Sites in Kuwait

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**Abstract: Problem statement:** The emission of pollutants from landfill sites in Kuwait is of major concern due to the associated adverse environmental and health impacts. There are 18 landfill sites in Kuwait which are contributing to the emission of atmospheric pollutants including; methane, carbon dioxide and Volatile Organic Compounds (VOCs). **Approach:** Determine the concentration and composition of VOCs in LFG emissions from two major landfill sites in Kuwait and to investigate the influence of the "*In-Situ Aerobic Stabilization*" on the reduction of VOCs emission. VOCs samples were collected during an intensive, short-term field sampling campaign conducted in 2010 where 50 individual volatile organic compounds were identified and quantified in landfill gas samples collected from the two landfill sites and the Project Area. **Results:** The concentration levels of VOCs were found to be significantly different within the same landfill site; however, the average total VOCs emissions were comparable between the two landfill sites. Concentration of total VOCs (i.e., sum of 50 compounds) in LFG emissions varied between 9.4-67.2 ppm in Jleeb Al-Shuyoukh landfill site and from 15.4-57.7 ppm in Al-Qurain landfill site. Annual emissions of the well-known five VOCs (i.e., benzene, toluene, ethylbenzene, m-, o- and p-xylenes and styrene) were also computed for each vent pipe from Jleeb Al-Shuyoukh landfill using the measured average concentrations and LFG flow rates. The results, if calculated in terms of the average  $\Sigma$ BTEX+S quantity emitted per vent pipe per year, showed that the magnitude of  $\Sigma$ BTEX+S emissions ranged between 0.108 -11.686 g y<sup>-1</sup>. **Conclusion:** The results of this pilot project demonstrated that the "*in-situ aerobic stabilization method*" applied on old solid waste deposits in the project area of Jleeb Al-Shuyoukh landfill can significantly reduce the average VOCs concentration in LFG emissions from high-productivity wells in the project area down to (6.3±1.6 ppm), whereas VOCs concentration in LFG emissions from high-productivity wells in Jleeb Al-Shuyoukh landfill and Al-Qurain landfill sites remained relatively high, 57.1±6.95 and 49.8±11.2 ppm, respectively.

**Key words:** VOCs, NMOCs, BTEX, Municipal Solid Waste, Landfills, LFG, emissions

### INTRODUCTION

After placement of Municipal Solid Wastes (MSW) in landfills; many biological, chemical and physical processes start to take place which would gradually lead to the emission of Landfill Gas (LFG) to air and leachates through ground (Awomeso *et al.*, 2010; Williams, 2005). A significant fraction of the biodegradable portion of MSW is ultimately converted to gaseous end-products during the anaerobic stabilization of solid waste organic fractions (Abushammala *et al.*, 2009). Usually, gas production begins within a year of waste placement and may

continue for as long as 50 years after landfill closure. Landfill Gas (LFG) consists usually of 50-60% CH<sub>4</sub>, 30-40 vol. %CO<sub>2</sub> and other trace gases (Wang-Yao *et al.*, 2006). Non-Methane Organic Compounds (NMOCs) usually make up also less than 1% of landfill gas. Various trace gases such as hydrogen sulfide, water vapor, ammonia and a variety of volatile Organic Compounds (VOCs) are also present in LFG. European research has identified that landfill gas is composed of 140 trace components of which 90 were common to all studied landfill sites (Parker *et al.*, 2002).

The emission of LFG is of major concern to local communities because of the bad smell and offensive

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odour as well as due to the various potential health hazards associated with toxic organic and inorganic compounds present in LFG. On the regional scale, LFG emissions are considered as a source of VOCs which contribute to the formation of photochemical oxidants including ground-level ozone (O<sub>3</sub>). On the global scale, the emission of methane in LFG contributes to greenhouse effects. The waste sector is considered a significant contributor to Greenhouse Gas (GHG) emissions accountable for approximately 5% of the global greenhouse budget (IPCC, 2006). Atmospheric methane gas (CH<sub>4</sub>) has more than doubled in concentration over the last 150 years (Stern *et al.*, 2007).

Numerous investigations have been conducted with the objective of characterizing landfill gas emissions. More than fifty different VOCs have been identified in landfill gases (Kim *et al.*, 2006). The list includes simple alkanes, olefins, aromatics and a wide array of chlorinated compounds. These VOCs include a number of known or suspected carcinogens (such as benzene, styrene and vinyl chloride). The concentrations of VOCs found in LFG typically range from a few parts per billion (ppb) to tens of thousands of ppb. Benzene, Toluene, Ethyl Benzene and Xylene (BTEX) compounds as well as methylated-and alkylated benzenes are frequently observed as trace contaminants in landfill gas.

The primary objective of the current study was to characterize VOCs emissions in LFG and to compare the composition and emission rates of VOCs between two major landfill sites in the State of Kuwait. The study also investigated the influence of in-situ aerobic stabilization of old solid waste deposits on the composition and concentration of VOCs in LFG emission.

## MATERIALS AND METHODS

**Landfill sites:** The most common practised disposal method in the State of Kuwait for Municipal Solid Waste (MSW) is burial in landfills (UNDP, 2002; AlAhmad *et al.*, 2003). Today, there are 18 landfills in Kuwait of which 14 sites are closed and 4 sites are still in operation (AlAhmad, 2009). Detailed information and data about these landfills, their waste input and composition or emissions measurements and characterization of VOCs in LFG do not exist. Due to the rapid development and the expansion in urban and residential areas in Kuwait, some of these landfills became on the borders of residential and urban areas, as is the case of Jleeb Al-Shuyoukh and Al-Qurain landfill sites (Fig. 1).

**Jleeb Al-Shuyoukh landfill:** The landfill of Jleeb Al-Shuyoukh is located in the south of Kuwait City close to the International Airport of Kuwait and adjacent to the south-eastern boarder of Abdullah Al-Mubarak residential area. This landfill site was licensed by

Kuwait Municipality to receive MSW from 1970-1993. The site is considered to be the largest MSW landfill in Kuwait where it encompasses approximately 6 square kilometres and the waste vertical profile varies in depth from 4-23 m. Approximately, about 20 million cubic meters of municipal solid waste and 3 million cubic meters of demolition waste were dumped during the operation period of the landfill. After a major burning incident of the landfill in 2002, a surface capping system with 1m-soil layer was installed. In 2006, 50 boreholes (depth up to 29 m) were drilled for measurement of landfill gas emissions. Measurements of LFG emission was started in March 2008 by the Environment Public Authority of Kuwait (KEPA).

In November 2008, a small area of Jleeb Al-Shuyoukh (576 m<sup>2</sup>) was used to conduct this research project in collaboration with the Department of Waste Management at Rostock University in Germany. Aerobic in-situ stabilization of old solid waste deposits (Heyer *et al.*, 2003; 2005; Cossu *et al.*, 2006; Zanetti, 2008) was applied in the "Project Area" of Jleeb Al-Shuyoukh landfill to examine how this method would improve the emission behaviour and composition of landfill gas under the local conditions of Kuwait (AlAhmad, 2009). In-situ aerobic stabilization of MSW aims to achieve accelerated reduction of the emission and settlement potentials, reduction of the technical and financial expenditures during the aftercare phase and a reduction of the aftercare period. Extensive scientific research have shown that a sustained improvement of the emission and settlement behaviour of the landfill through aerobic in-situ stabilization measures can be achieved when the process technology is adapted to the local conditions of the landfill body and operated in a qualified manner (Spillmann *et al.*, 2001; Heyer *et al.*, 2003; 2005).

**Al-Qurain landfill site:** As shown in Fig. 1 above, this site has become over the past years entirely surrounded by residential areas from all sides due to the expansion of nearby residential areas. The area of Al-Qurain landfill was originally used for dumping of municipal and construction waste from 1970-1985. The volume of the landfill is approximately 5 million m<sup>3</sup> and the maximum depth of waste is 24 m. The surface is capped with a 1m soil layer. The landfill is equipped with an active LFG venting and collection system, a flare for burning-off LFG and a pre-treatment plant for leachate. The gas venting system has been in operation since 2005.

**Sample collection:** During the period May-August 2010, twenty eight samples were collected from selected monitoring wells (boreholes) in Jleeb landfill, the "Project Area" in Jleeb landfill and from Al-Qurain landfill site (Fig. 2 and 3 for the locations of boreholes used for sampling of VOCs).

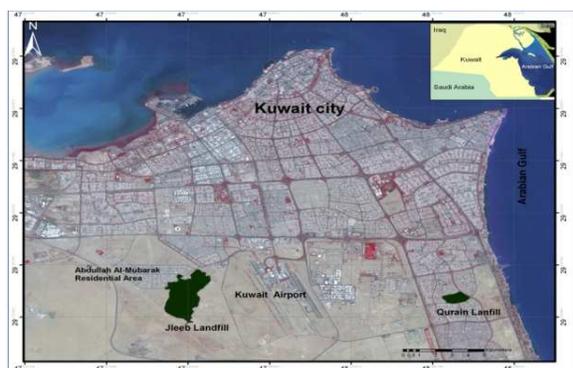


Fig. 1: Satellite image of Kuwait City (SPOT, April 2010) showing the location of the two landfill sites (areas coloured in dark green)



Fig. 2: Location of boreholes used for the collection of VOCs samples from Jleeb landfill site



Fig. 3: Location of boreholes used for the collection of VOCs samples from Al-Qurain landfill

Table 1 gives short descriptions of the boreholes used for sampling. Boreholes 4 and 35 in Jleeb landfill were chosen to represent the native soils in the area with no waste buried underneath.

Boreholes 21 and 46 in Jleeb Al-Shuyoukh landfill and borehole S17 in Al-Qurain landfill were chosen to represent wells of low methane productivity, whereas boreholes 16 and 49 in Jleeb landfill and borehole S12 in Al-Qurain landfill were chosen to represent wells of

high methane productivity (i.e., reaching a mature methanization stage). Borehole No 18 in Jleeb landfill was chosen following the aeration experiment (i.e., in-situ aerobic stabilization of buried wastes) applied in the in the “Project Area”.

Prior to the sampling of VOCs, the borehole valve was opened and connected to a hand-held portable device (GA 2000 Plus infrared gas analyser, Geotechnical Instruments-UK) for the in-situ measurement of CH<sub>4</sub>, CO<sub>2</sub>, CO, O<sub>2</sub> and temperature in LFG. Sampling of VOCs was achieved using a clean Tedlar bag (1 L) and a small vacuum pump.

**Sample analysis:** Collected samples were brought to the analytical laboratory for the analysis of Volatile Organic Compounds (VOCs) in landfill gas. Fifty individual VOCs were identified and quantified in this study, ranging from simple aliphatic and aromatic hydrocarbons to di- and tri-methylated benzenes. The target volatile organic compounds identified and quantified in this study are listed in Table 2.

Analysis of VOCs in the collected gas samples was accomplished by following USEPA Method PAMS (Photochemical Assessment Monitoring Stations). The analytical system included a gas chromatography system (Perkin Elmer) equipped with flame ionization detector (GC/FID). The Gas Chromatography system (GC) was also equipped with a perkin elmer Automatic Thermal Desorber (ATD 400). The VOC samples contained in Tedlar bags were analyzed by introducing them into the GC/FID system with the aid of Peltier Cooling (PC) and the Thermal Desorption (TD) method (PC/TD system). Using this PC/TD system, the target VOC in LFG samples were then pre-concentrated in a liquid N<sub>2</sub>-free cold trap (packed with both Carbosil adsorbent) at -15°C. Trapped VOC were then released thermally by heating the cold trap for 2 min at 320°C.

A 30 m GC capillary column (BP1) was used for the chromatographic separation of the different VOCs. After elution from the capillary column, identification of individual VOCs compounds was achieved by the Flame Ionization Detector (GC/FID) connected at the end of the capillary column.

Figure 4 and 5 show the GC/FID chromatograms recorded during the identification of light and heavy molecular weight VOCs in LFG samples, respectively. Appropriate calibration procedures were employed to ensure GC/FID reliability and accuracy. The GC/FID system was calibrated using a standard calibration cylinder (Spectra Gases, UK) containing all light and heavy molecular weight VOCs at a concentration of 100 ppb each. Detection limits for all VOCs was about 5 ppb.

Table 1: Description of VOCs sampling locations in Jleeb and Al-Qurain Landfill sites

Landfill site	Borehole no.	Type	Max CH4 productivity during sampling	No. of samples
Jleeb Al-Shuyoukh	BH 4 and 35	Native soil	CH <sub>4</sub> <2%	4
	BH 21 and 46	No buried waste underneath	Zero-productivity	
		Waste buried under 1m-soil layer	CH <sub>4</sub> = 20-30% Low-productivity	4
	BH16 and 49	Waste buried under 1m-soil layer	CH <sub>4</sub> = 50-60% High-productivity	4
Al-Qurain	BH 18 Project area "In-situ aerobic stabilization"	Waste buried under 1m-soil layer	CH <sub>4</sub> = < 3.3% After aeration	8
	BH S17 Under 1m-soil layer (LFG collection)	Waste buried under 1m-soil layer	CH <sub>4</sub> = 20-30% Low-productivity	4
	BH S12 Under 1m-soil layer (LFG collection)	Waste buried under 1m-soil layer	CH <sub>4</sub> = 50-60% High-productivity	4

Table 2: VOCs identified and quantified in LFG samples

1	Ethylene	18	N-Hexane	35	M/P Xylene
2	Propane	19	MethylCyclopentane	36	Styrene
3	Propylene	20	2,4 DimethylPentane	37	O-Xylene
4	Iso-Butane	21	Benzene	38	N-Nonane
5	N-Butane	22	CycloHexane	39	IsoPropylBenzene
6	Acetylene	23	2-MethylHexane	40	N-PropylBenzene
7	1-Butene	24	2,3DimethylPentane	41	M-EthylToluene
8	Trans-2Butene	25	3-MethylHexane	42	P-EthylToluene
9	N-Pentane	26	2,2,4TrimethylPentane	43	1,3,5TriMethylBenzene
10	Trans-2Pentane	27	N-Heptane	44	O-EthylToluene
11	1-Pentene	28	MethylCycloHexane	45	1,2,4TriMethylBenzene
12	Cis-2Pentene	29	2,3,4TriMethylPentane	46	N-Decane
13	2,2 DiMethylButane	30	Toluene	47	1,2,3TriMethylBenzene
14	2,3 DimethylButane	31	2-MethylHeptane	48	M-DiethylBenzene
15	2 MethylPentane	32	3-MethylHeptane	49	P-DiethylBenzene
16	Isoprene	33	N-Octane	50	N-Undecane
17	1-Hexene	34	EthylBenzene		

## RESULTS AND DISCUSSION

**Composition and concentrations of VOCs in LFG:** Figure 6 and 7 compare the average concentrations of individual VOCs (50 compounds) measured in LFG samples collected from the different boreholes in the two landfill sites. It is evident from Fig. 7 and 8 that the composition of VOCs and the magnitude of measured concentrations are very much comparable between the high-productivity wells in the two landfill sites in Al-Jleeb and Al-Qurain where the correlation factor is relatively high ( $R^2 = 0.7966$ ). The highest concentrations of VOCs in all sampling sites were observed for; styrene, *m*-methyltoluene and diethylatedbenzenes.

Table 3 summarizes the results of total VOCs concentrations (sum of 50 compounds) measured in LFG emissions from the monitoring wells in Jleeb Al-Shuyoukh and Al-Qurain landfill sites. Concentrations of total VOCs ranged from as low as  $1.3 \pm 0.5$  ppm in wells located in native soil areas up to  $57.1 \pm 6.9$  ppm and  $49.8 \pm 11.2$  in wells of high-productivity areas in both of Jleeb Al-Shuyoukh and Al-Qurain landfill sites, respectively.

The result show that the total VOCs emission from the project area (i.e., borehole No 18) is about one-half of the emission from the low-productivity wells in Jleeb landfill and about one-tenth of total VOCs emission from high-productivity wells. This significant reduction in VOCs emissions from the project area can be attributed to the high and rapid biological aerobic reactivity taking place in the project area. If this significant difference is converted into percent reduction in total VOCs emission relative to the emission from the high-productivity wells, then the in-situ aerobic stabilization can speed up the decomposition of the biodegradable organic wastes and significantly reduce VOCs emissions by about 89% in comparison with the slow anaerobic biological reactions which usually needs several tens of years to decompose the buried wastes.

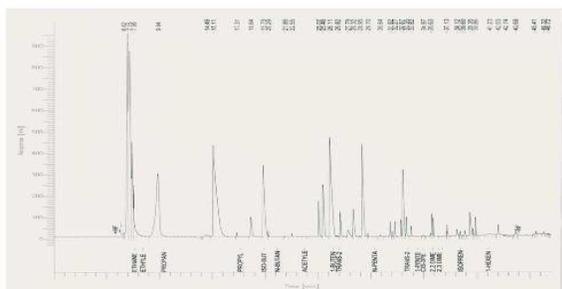


Fig. 4: GC/FID chromatogram of light VOCs identified in LFG samples

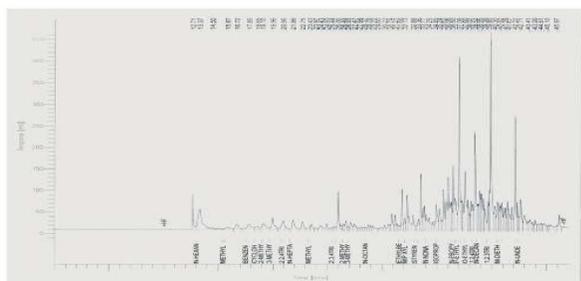


Fig. 5: GC/FID chromatogram of heavy VOCs identified in LFG samples

**The distribution of major aromatic VOCs in LFG emissions:** Table 4 represents a statistical summary of major aromatic VOCs concentrations measured in this study (i.e., benzene; toluene; ethylbenzene; *m*-, *p*- and *o*-xylenes and styrene). Benzene concentrations ranged from as low as 5 ppb in LFG emissions from low-productivity wells and up to 252.1 ppb in LFG emissions from high-productivity wells. Xylene isomers (*meta*, *para* and *ortho*) and styrene were present in LFG emissions at much higher concentrations than benzene, toluene and ethylbenzene. The concentration of styrene reached as high as 4718.0 and 4057.8 ppb in high-productivity wells in Jleeb Al-Shuyoukh landfill and Al-Qurain landfill, respectively. Schrap and Al-Mutairi (2010) reported the concentrations

of 13 VOCs including BTEX and styrene in LFG emissions from Jleeb Al-Shuyoukh landfill. Table 4 compares the results of BTEX and styrene measurements

obtained in this study with those reported in the literature (Schrapp and Al-Mutairi, 2010; Al-Mutairi, 2004; Kim *et al.*, 2006).

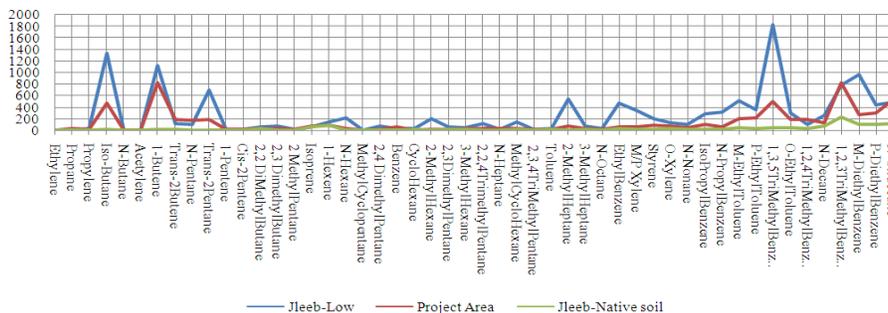


Fig. 6: Comparison of VOCs concentrations between low-productivity wells, native soil wells and the Project Area wells in Jleeb Al-Shuyoukh landfill (units are in ppb)

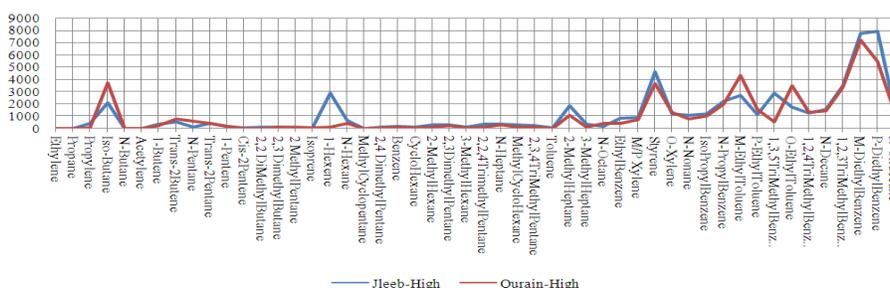


Fig. 7: Comparison of VOCs concentrations between Jleeb Al-Shuyoukh and Al-Qurain high-productivity wells (units are in ppb)

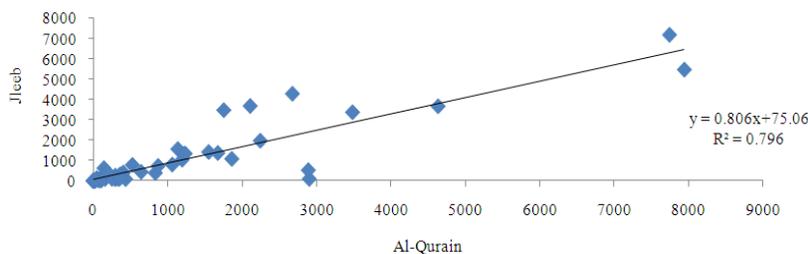


Fig. 8: Correlation of VOCs concentrations between Jleeb Al-Shuyoukh and Al-Qurain high-productivity wells (units in ppb)

Table 3: A statistical summary of VOCs concentrations measured in LFG emissions

Landfill Site	Borehole No.	Productivity	Total* VOCs concentration (ppm)	
			Mean ± STD	Range (Min-Max)
Jleeb Al-Shuyoukh	BH 4 and 35	CH <sub>4</sub> <2%	1.3±0.5	(0.78-1.7)
	BH 21 and 46	Zero-productivity	13.1±2.9	(9.4-15.7)
	BH16 and 49	low-productivity	57.1±6.9	(51.9-67.2)
Al-Qurain	BH 18, project area	high-productivity	6.3±1.6	(4.7-9.1)
	"In-situ aerobic stabilization" BH S17	CH <sub>4</sub> = < 3.3%		
	BH S12	low-productivity	18.8±4.8	(15.4-22.1)
		CH <sub>4</sub> = 50-60% high-productivity	49.8±11.2	(41.2- 57.7)

\*: Sum of 50 VOCs

Table 4: A statistical summary of major aromatic VOCs concentrations measured in Jleeb Al-Shuyoukh and Al-Qurain landfills

Landfill site/ sampling well	Concentration of Major Aromatic VOCs (in ppb)							Ratio B/T
	Benzene	Toluene	Ethyl Benzene	m&p-Xylene	o-Xylene	Styrene	ΣBTEX+S <sup>1</sup>	
Jleeb Al-Shuyoukh (Native soil well)	3.9±7.8 <sup>2</sup> (5.0-15.7) <sup>3</sup>	15.7±10.9 (5.0- 23.8)	30.5±20.2 (11.4-48.0)	20.5±8.1 (12.2-31.2)	31.7±13.0 (18.2-47.7)	17.7±6.3 (11.0-25.6)	125.1±53.3 (66.1-181.2)	0.6±0.4 (0.2-1.0)
Jleeb Al-Shuyoukh (Low-productivity wells)	21.8±36.2 (5.0-75.5)	24.3±8.4 (16.2-32.4)	462.2±374.3 (125.4-824.5)	339.0±292.7 (76.8-621.0)	124.1±59.3 (86.7-212.1)	195.8±45.9 (154.6-260.2)	1169.6±706.7 (504.6-1939.4)	0.8±1.0 (0.3-2.3)
Jleeb Al-Shuyoukh (High-productivity wells)	160.0±78.2 (72.1-252.1)	35.3±17.1 (18.3-50.6)	836.6±324.4 (495.2-1178.8)	874.0±140.0 (683.4-1010.2)	1213.1±484.5 (598.9-1659.2)	4633.2±103.2 (4488.2-4718.0)	7752.3±935.5 (6557.5-8565.3)	5.6±3.7 (1.4-10.5)
Jleeb Al-Shuyoukh (Project Area)	53.0±14.7 (33.2-76.3)	8.9±2.9 (6.3-15.0)	57.8±13.1 (38.1-74.2)	56.4±19.5 (37.3-87.5)	67.3±29.6 (36.3-117.3)	82.9±47.2 (43.9-161.0)	326.5±78.0 (239.8-445.3)	6.1±1.1 (5.0-8.2)
Al-Qurain (Low-productivity well)	9.5±6.3 (5.0-14.0)	6.0±1.4 (5.0 - 7.0)	296.1±106.4 (220.9-371.3)	430.0±127.9 (339.6-520.2)	478.7±245.8 (304.9-652.5)	117.4±40.8 (88.6-146.3)	1337.3±525.8 (966.0-1709.6)	1.8±1.5 (0.7-2.8)
Al-Qurain (High-productivity well)	94.5±62.6 (50.2-138.7)	29.0±6.9 (24.1-33.8)	391.4±21.5 (376.2-406.6)	732.7±129.4 (641.2-824.2)	1320.9±271.2 (1129.1-1512.7)	3661.0±561.5 (3264.2-4057.8)	6229.4±1038.9 (5494.8-6964.0)	3.6±3.0 (1.5-5.8)
Jleeb Al-Shuyoukh <sup>4</sup> Summer (2004)	767	17333	821	NM <sup>5</sup>	NM	519	19440	0.04
Winter (2004)	490	12000	420	NM	NM	282	13192	0.04
Korea <sup>6</sup>								
Site A (NJ)	31.8	259.0	NM	10.4	45	NM	346.2	0.12
Site B (WJ)	924.0	2610.0	982.0	1045.0	NM	91.5	5652.5	0.35
Site D (HC)	828.0	1808.0	1264.0	946.0	1269.0	66.0	6181.0	0.46
Site E (NH)	117.0	21.9	53.7	43.2	48.9	248.0	532.7	5.30

<sup>1</sup> ΣBTEX+S: Sum of benzene; toluene; ethylbenzene; m, p and o-xylenes and styrene. <sup>2</sup> Mean ± standard deviation. <sup>3</sup>Concentration range (min-max). <sup>4</sup>: Schrapp and Al-Mutairi (2010): Only mean values were reported. <sup>5</sup>:NM: not measured. <sup>6</sup>: (Kim *et al.*, 2006)

Table 5: A statistical summary of major aromatic VOCs fluxes calculated for each vent pipe in Jleeb Al-Shuyoukh landfill

Landfill site/sampling well	VOCs fluxes (g/year)						
	Benzene	Toluene	EthylBenzene	m and p-Xylene	o-Xylene	Styrene	ΣBTEX+S <sup>1</sup>
Jleeb Al-Shuyoukh (Low-productivity wells)	0.016±0.023 <sup>2</sup> (0.003-0.051) <sup>3</sup>	0.019±0.007 (0.013-0.026)	0.432±0.354 (0.117- 0.770)	0.308±0.266 (0.070-0.564)	0.113±0.054 (0.079-0.193)	0.175±0.041 (0.138-0.232)	1.062±0.645 (0.455-1.758)
Jleeb Al-Shuyoukh (High-productivity wells)	0.163±0.080 (0.074-0.257)	0.042±0.021 (0.022-0.061)	1.192±0.462 (0.705-1.678)	1.210±0.194 (0.946-1.399)	1.682±0.671 (0.829-2.297)	6.294±0.140 (6.097-6.409)	10.58±1.299 (8.927-11.686)
Jleeb Al-Shuyoukh (Project Area)	0.019±0.005 (0.012-0.027)	0.004±0.001 (0.003-0.006)	0.029±0.006 (0.019-0.037)	0.027±0.009 (0.018-0.042)	0.032±0.014 (0.017-0.056)	0.039±0.022 (0.021-0.076)	0.150±0.038 (0.108-0.206)

<sup>1</sup> ΣBTEX+S: Sum of benzene; toluene; ethylbenzene; m,p,o-xylenes and styrene. <sup>2</sup> Mean ± standard deviation. <sup>3</sup>Concentration range (min- max)

As shown in Table 4 and Fig. 9 that the sum of BTEX and styrene emissions (ΣBTEX+S) was comparable between Jleeb Al-Shuyoukh high-productivity wells (7752.3 ppb) and Al-Qurain high-productivity wells (6229.4 ppb) and also with those reported for sites B and D in Korea, 5652.5 ppb and 6181 ppb, respectively.

ΣBTEX+S emission from high-productivity wells in Jleeb Al-Shuyoukh are almost half of those calculated for BTEX and styrene measured in 2004 (Schrapp and Al-Mutairi, 2010). ΣBTEX+S emission from Jleeb Al-Shuyoukh low-productivity wells (1169.6 ppb) was also comparable with ΣBTEX+S emission from Al-Qurain low-productivity wells (1337.3 ppb). Interestingly, the average emission of ΣBTEX+S from monitoring wells in the project area was significantly reduced down to 326.5 ppb which is only 200 ppb higher than the measured ΣBTEX+S emissions from the native soil boreholes in the background of Jleeb Al-Shuyoukh landfill site.

The Benzene-to-Toluene ratio (B/T) is widely used in source apportionment studies to evaluate VOC emission characteristics from different sources. It has been reported that the B/T ratio was between 0.015 and 0.11 for landfill gas, 0.5 for vehicle exhaust gas and between 0.27 and 0.5 for typical urban atmospheric environment (Dincer *et al.*, 2006). Other studies have also reported B/T ratios between 0.01 and 0.2 for landfill gas (Kim *et al.*, 2006). Kim *et al.* (2006) measured

VOCs emissions from five landfill sites in Korea and reported that B/T ratios varied significantly between 0.12 and 5.3. Urase *et al.* (2008) reported B/T ratio as high as 8 at a location in a landfill site in Tokyo-Japan.

As shown in Table 4, in the present study we observed low B/T ratios in the native soil wells and also in low-productivity wells in Jleeb Al-Shuyoukh landfill site of 0.6 and 0.8, respectively; whereas, higher B/T ratios of 6.1 and 5.6 were observed in the project area “In-situ aerobic stabilization” and in high-productivity wells in Jleeb Al-Shuyoukh and AlQurain landfill, respectively. These high B/T ratios in the project area and in the high-productivity wells can be attributed to the higher biological reactivity and reactions taking place in the vicinity of these. The temperature inside the waste layer is known to go up to 80°C occasionally. The exposure of the plastics in solid waste layer to such high temperature is probably one of the reasons for the release of VOCs from solid waste disposal sites. Figure 10 also shows that there was a good correlation (R<sup>2</sup> = 0.9242) between B/T ratios and ΣBTEX+S emissions for Jleeb Al-Shuyoukh and Al-Qurain high-productivity wells which further demonstrates the similarity in the chemical and biological processes, types and age of buried wastes as well as other local conditions between the two landfills leading to similar composition and concentrations of VOCs in LFG emissions.

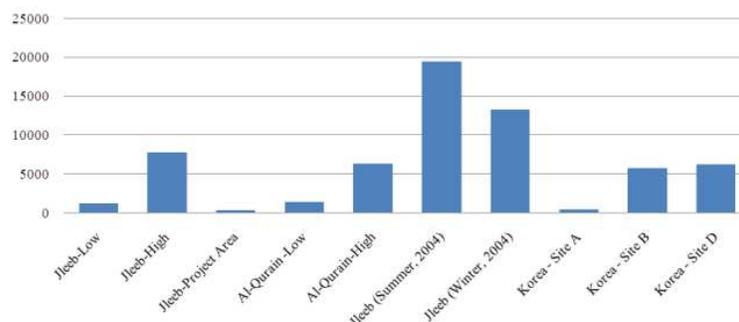


Fig. 9: Comparison of ΣBTEX+Styrene measured in this study with those reported in the literature (in ppb)

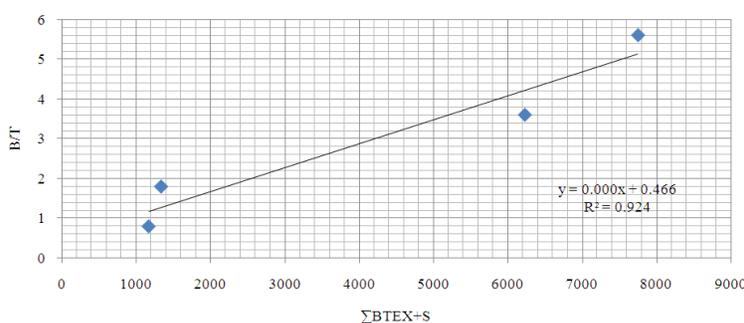


Fig. 10: Correlation between B/T and ΣBTEX+S in Jleeb Al-Shuyoukh and Al-Qurain

**Estimation of VOCs annual emission rates:** One of the objectives of the present study includes accurate identification and quantification of VOCs emissions from the two major landfill sites in Kuwait (i.e., Jleeb Al-Shuyoukh and Al-Qurain). The availability of this kind of information can help in evaluating the emission potential of a given landfill environment. For this purpose, the major five VOCs (i.e., benzene; toluene; ethylbenzene; m-, p- and o-xylenes and styrene) were computed for each sampled monitoring well in Jleeb Al-Shuyoukh landfill using their concentrations and the concurrently determined flow rates of LFG.

However, as our estimation is based on a relatively limited quantity of data sets such results may only be used at this stage as rough estimates for the extent of VOC emissions from landfill sites in Kuwait. Table 5 lists the results calculated in terms of the average ΣBTEX+S quantity emitted per vent pipe per year which showed that the magnitude of their annual emission rates can vary substantially, with the values ranging between 0.108-11.686 g y<sup>-1</sup>.

## CONCLUSION

During this study it was possible for the first time in Kuwait to identify and quantify 50 Volatile Organic

Compounds (VOCs) in LFG emissions from two old landfill sites in Kuwait. The compounds identified included the well-known four aromatic VOCs; Benzene, Toluene, Ethylbenzene and *o*-, *m* and *p*-Xylenes (BTEX). Styrene was also identified and its concentration level was the highest amongst aromatic VOCs. Concentrations of total VOCs (i.e., sum of 50 compounds) in LFG emissions varied between 9.4-67.2 ppm in Jleeb Al-Shuyoukh landfill site and from 15.4-57.7 ppm in Al-Qurain landfill site.

The results obtained in this study demonstrated that the concentration levels of VOCs were found to be significantly different within the same landfill site depending on the reactivity and productivity of the biological decomposition processes of buried wastes. In addition, the results also demonstrated that total VOCs emissions were comparable between the two landfill sites.

This study demonstrated that the “in-situ aerobic stabilization method” applied in the project area of Jleeb Al-Shuyoukh landfill for the treatment of old waste deposits in landfills can significantly reduce the emission of VOCs in LFG by as much as 89%.

## ACKNOWLEDGMENT

This study was supported by the University of Rostock in Germany as part of PhD research at the

Department of Waste Management/Institute of Environmental Engineering. The authors thank the Environment Public Authority in Kuwait for the analysis of leachates and groundwater samples in their laboratories. Thanks are due to the "Landfill Rehabilitation Committee" in Kuwait (the Triple-Committee) for their support of this work. Thanks are also due to Mr. Ismail Abdulghani and Mr. Faysal Rageb for their technical assistance and to Mr. Jasim Al-Hasawi for his administrative assistance.

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